Has Blending Compromised Cepheid-Based Determinations of the Extragalactic Distance Scale?

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ABSTRACT

We examine the suggestion that half of the *HST Key Project*- and *Sandage/Saha*-observed galaxies have had their distances systematically underestimated, by $0.1 - 0.3$ mag in the distance modulus, due to the underappreciated influence of stellar profile blending on the WFC chips. The signature of such an effect would be a systematic trend in (i) the Type Ia supernovae corrected peak luminosity and (ii) the Tully-Fisher residuals, with increasing calibrator distance, and (iii) a differential offset between PC and WFC distance moduli, within the same galaxy. The absence of a trend would be expected if blending were negligible (as has been inherently assumed in the analyses of the aforementioned teams). We adopt a functional form for the predicted influence of blending that is consistent with the models of Mochejska et al. and Stanek & Udalski, and demonstrate that the expected correlation with distance predicted by these studies is not supported by the data. We conclude that the Cepheid-based extragalactic distance scale has *not* been severely compromised by the neglect of blending.

Subject headings: Cepheids — distance scale — galaxies: distances and redshifts

1. Introduction

In recent papers, Mochejska et al. (1999) and Stanek & Udalski (1999) suggest that blending of stellar images on *HST* WFC images has led the *HST Key Project on the Extragalactic Distance Scale* (Gibson et al. 2000; Sakai et al. 2000) and *Type Ia Supernovae Calibration Team* (Saha et al. 1999; hereafter *Sandage/Saha*) to systematically underestimate the distance to the galaxies in their sample, resulting in an overestimate of the Hubble Constant. The magnitude of the predicted effect increases with galaxy distance, ranging from 0.05 mag for the nearest galaxies to 0.35 mag for the most distant galaxies in the samples (i.e., distance modulus $\mu_\circ \approx 32$). To date, blending has been assumed to be a negligible contributor to the Cepheid distance scale systematic error budget. The results of Mochejska et al. and Stanek & Udalski, however, suggest that both Hubble Constant teams overestimated $H_\circ$ by $5-10\%$. Since the magnitude of this suggested effect is as large as the entire quoted standard error budget (e.g., Table 6 of Sakai et al. 2000), it is crucial that further empirical tests of the Mochejska et al. and Stanek & Udalski blending scenario be made.

In Section 2, we describe a simple, yet heretofore neglected, empirical test of the Mochejska et al. (1999) and Stanek & Udalski (1999) blending scenario. By examining the distribution of V-band corrected peak luminosities for the 8 Type Ia supernovae (SNe) calibrators used in the $H_\circ$ analysis by Gibson et al. (2000), the distribution of I- and H-band Tully-Fisher residuals, for the 18 *HST*-observed calibrators used by Sakai et al. (2000), and the comparison of Planetary Camera (PC) and Wide Field Camera (WFC) distance moduli for five suitable Virgo and Fornax Cluster galaxies, we demonstrate that the systematic trend predicted by Mochejska et al. and Stanek & Udalski is *not* supported by the data. The absence of a trend is consistent with the inherent assumptions of both *HST* Hubble Constant teams. Section 3 summarizes our findings.

2. Analysis

We quantify the predicted influence that blending has upon Cepheid-based distance determinations by employing the models of Stanek & Udalski (1999, Figure 2); their ">5%" cutoff models (i.e., a minimum of 5% of the mean flux of a Cepheid is required for a star to be included as a blend) are suitable for our needs. The blending difference $\Delta\mu_\circ$ between what Stanek & Udalski label the "true" distance, and that "measured" by the *HST Key Project* and *Sandage/Saha Team* is represented by the following functional

form:

$$\Delta\mu_\circ \equiv \mu_\circ(\text{true}) - \mu_\circ(\text{measured}) \approx 0.002\, d^{1.62} \quad \text{mag}, \tag{1}$$

where d is the galaxy distance in Mpc – i.e., the "measured" distance modulus is hypothesized to systematically underestimate the true modulus. The magnitude of this effect is 0.1 mag at $d = 12$ Mpc, and 0.3 mag at $d = 23$ Mpc.

A direct consequence of blending of the magnitude predicted by Stanek & Udalski (1999) and Mochejska et al. (1999) (for the remainder of this paper we shall refer to these papers collectively as Stanek et al.) is that a systematic trend in the distribution of both corrected Type Ia SNe peak luminosities – assumed to be standard candles – and Tully-Fisher residuals, as a function of calibrator distance, should result. Empirically, we should observe the corrected peak luminosities and the T-F residuals shift to an apparently lower luminosity with increasing calibrator distance. This test was not included in the Mochejska et al. or Stanek & Udalski analyses.

In Figure 1, the corrected V-band peak luminosities of the eight Type Ia SNe calibrators (Gibson et al. 2000) are shown as a function of the "measured" $\mu_\circ$; the three circled points refer to those SNe with poorer-quality light curves and/or photometry. We have calculated least-square fits with and without their inclusion. The solid horizontal curve – the weighted mean of all eight points – represents the locus about which symmetric scatter is expected, in the absence of significant blending effects. The dotted curve shows the Stanek et al. blending prediction, given by equation 1; if blending is important, this dotted curve should be the locus about which the calibrators scatter symmetrically. A straight-line fit, with a slope statistically indistinguishable from zero (as assumed in the previous distance-scale analyses), provides an excellent representation of the data. (In fact, the reduced chi-square values χ_ν for the straight-line fits are so low, $\sim 0.2 - 0.4$, that one would ordinarily conclude that the error bars on the data points have been overestimated. Monte Carlo simulations of the data set suggest this overestimate is a factor of roughly $1.4 - 2$.)

EDITOR: PLACE FIGURE 1 HERE.

If the zero-point of the blending model curve is taken to be the corrected V-band peak luminosity zero-point defined by the "no blending" value, then the blending prediction is inconsistent with the data at the 2.2σ level (this is true for any zero-point fainter than $\mathrm{M}_V^{\mathrm{corr,ZP}}$≈-19.5), using either the five high-quality calibrators or the full set of eight. However, if blending is important, there is no *a priori* justification for

assuming that the zero point of the blending model curve in Figure 1 is equal to the "no-blending" value. If we relax this assumption and allow $M_V^{\rm corr,ZP}$ to vary, χ_ν for the Stanek et al. blending model reaches an acceptable value for a zero point $M_V^{\rm corr,ZP} = -19.62 \pm 0.1$. The dotted curve of Figure 1 shows this best-fit blending solution. While this latter fit is not formally as significant as the "no blending" straight line, it is excluded only at the $\sim 1\sigma$ level[1].

In allowing $M_V^{\rm corr,ZP}$ to vary freely, however, we are ignoring another constraint imposed by the observations, namely, the observed tight clustering of the five high-quality data points about a zero-slope line with $M_V^{\rm corr,ZP} = -19.46$. We have therefore carried out Monte Carlo simulations of the data set, assuming that the blending model is correct, with the distribution of points in $\mu_\circ$ chosen to match the data. The dispersion of the points about the blending model curve is chosen to be either equal to the typical error bar, or that value reduced by a factor of 1.4, in case the errors have been overestimated. We generated a large number of synthetic data sets of five supernovae, and then asked in what fraction of the data sets at least four out of the five fall as closely to a zero-slope line (with any zero-point) as the actual data. This fraction is about 5% using the actual errors and about 12% for the reduced dispersion. However, unsurprisingly, the probability that the data points will scatter about a zero-slope line with an intercept close to -19.46 drops rapidly as we move the zero point away from this value. For all values of $M_V^{\rm corr,ZP}$ for which a reasonable fit of the blending model is possible, the probability of reproducing this aspect of the data (i.e., of obtaining a zero-slope line with an intercept within 0.1 of -19.46) is less than a few percent (for either choice of dispersion), so that we again rule out the blending model at the $\sim 2\sigma$ level.

In Figure 2, we show the distribution of I- (left panel) and H-band (right panel) Tully-Fisher residuals with $\mu_\circ$, for the 18 *HST*-observed calibrators used by Sakai et al. (2000). The three ground-based calibrators are not included in the formal blending analysis, since equation 1 holds only for blended *HST* WFC frames, and not these particular ground-based datasets. The solid and dotted curves in Figure 2 have the same meaning as those shown in Figure 1; although the blending curve is shown with an intercept of zero, this is not necessarily the case, and the curve has been included only to show the shape of the blending prediction. In calculating least-square fits to the data points, we have assumed an intrinsic dispersion of 0.2 mag in the I- and H-band Tully-Fisher relations (Sakai et al. 2000).

[1]If the error bars have been overestimated, the range of $M_V^{\rm corr,ZP}$ for which acceptable solutions can be found for the blending model shrinks and the quality of the fit is lower; however, the blending model is ruled out at the 2σ level, regardless of zero-point, only if the overestimate is as large as a factor of two.

EDITOR: PLACE FIGURE 2 HERE.

As with the ground-based calibrators, we have not included NGC 4603 (in the Cen30 cluster) in our analysis, despite Newman et al.'s (1999) recent Cepheid distance determination of $\mu_\circ = 32.61 \pm 0.11\,$mag. In combination with the H-band photometry and 21cm line-width measurements tabulated by Han (1992), the Newman et al. modulus implies an H-band Tully-Fisher residual of $\sim$1.3$\pm$0.3 mag - i.e., NGC 4603 is *extremely* discrepant with the H-band Tully-Fisher relation presented in Sakai et al. (2000, equation 10). This discrepancy *is* in the direction expected for data compromised by severe blending.

Two crucial points need to be mentioned here, however: first, the Stanek et al. functional form for blending (equation 1) was based upon Cepheids on the WFC chips only; in contrast, the Newman et al. analysis included only Cepheid candidates found on the higher-resolution PC chip. The functional form for PC Cepheid blending would naturally lie between the two curves shown in Figure 2 - i.e., the implied H-band residual for NGC 4603 is highly discrepant with both the no-blending assumption *and* the Stanek et al. scenario, *assuming the Newman et al. modulus is correct.* Second, and more importantly, NGC 4603 is *not* employed as an $H_\circ$ calibrator, so whether or not its Cepheid distance has been underestimated is irrelevant in terms of the $H_\circ$ analyses of the *HST Key Project* and *Sandage/Saha*. We speculate that the Newman et al. result has indeed been compromised by extreme crowding effects, such that its distance has been underestimated by $\gtrsim$1 mag. This would require an intrinsic stellar background contamination several times greater than the LMC and M31 fields employed by Stanek et al. in deriving equation 1, which themselves are already several times greater than the typical *HST Key Project* field. To reiterate, this has *no* impact upon $H_\circ$, as NGC 4603 has not been used as a calibrator.

The inferior statistics associated with the Tully-Fisher residuals (in both bands) do not allow us to make any unequivocal statements regarding the Stanek et al. blending scenario.[2] While the best-fitting

[2]Ferrarese et al. (2000; Appendix A) present an analog to our Figure 2, but conclude that the Stanek et al. blending hypothesis can be excluded at the $1.85\,\sigma$ level, in apparent contradiction with our analysis. The source of the discrepancy can be traced to the fact that Ferrarese et al. neglect the uncertainties associated with each of the H-band Tully-Fisher residuals shown in their Figure 18 - i.e., they performed a least squares fit to the twenty points shown, ignoring the plotted error bars. Doing so does indeed return a slope in the opposite direction predicted by Stanek et al., but the conclusion to be drawn by such an approach is not that Stanek et al. can be ruled out at the $1.85\,\sigma$ level, but that the assumption of "no blending" (as assumed

straight lines actually have the opposite slope to the blending prediction, both the blending model and a zero-slope line differ from the best-fit lines at most at the 1σ level. More data at larger values of $\mu_\circ$, where there is a larger difference between the blending and no-blending models, are needed. At present all we can state is that the Tully-Fisher residuals do not provide any support for the claim that the distance scale has been systematically underestimated due to the effects of stellar blending.

Independent of these *direct* tests of the Stanek et al. blending scenario, there exists a more straightforward *differential* test. Because of the factor of two improvement in spatial resolution between the Planetary Camera (0.046 arcsec/pixel) and the Wide Field Camera (0.1 arcsec/pixel), if Stanek et al. are correct, a systematic difference should be seen between the distance moduli based upon PC Cepheids alone, $\mu_\circ$(PC), and those based upon WFC Cepheids alone, $\mu_\circ$(WF). The sense of the systematic offsest should be such that $\mu_\circ(\mathrm{PC})>\mu_\circ(\mathrm{WF})$. For galaxies in the Virgo or Fornax Clusters, under the Stanek et al. blending hypothesis, the measured $\mu_\circ$(WF) should underestimate the true value by 0.16 mag, while the measured $\mu_\circ$(PC) would be underestimated by only 0.05 mag - i.e., there should be a 0.11 mag differential offset between the measured $\mu_\circ$(PC) and $\mu_\circ$(WF). This prediction is independent of any arguments pertaining to Tully-Fisher residuals or Type Ia SNe corrected peak luminosities (Figures 1 and 2).

An examination of the full *HST Key Project* and *Sandage/Saha* samples showed that only five galaxies met the criteria necessary to perform the above differential test. First, we required the galaxy be distant enough ($\mu_\circ > 30.7$) to show at least a 0.1 mag differential effect between $\mu_\circ$(PC) and $\mu_\circ$(WF) and, second, we insisted there be at least four high-quality Cepheids on the PC, in order to define a useful period-luminosity relation.[3] Table 1 lists the five galaxies (four in Virgo and one in Fornax) employed in our differential test (NGC 1365, 4536, 4496A, 4321, and 4548). Recall, the predicted magnitude of $\mu_\circ(\mathrm{PC})-\mu_\circ(\mathrm{WF})$, for Virgo/Fornax galaxies, is +0.11 mag. As can be seen in Table 1, though, the weighted mean offset between $\mu_\circ$(PC) and $\mu_\circ$(WF), for these five galaxies, is $+0.002\pm0.049$. In other words, this differential test allows us to reject the Stanek et al. blending scenario at the $2.2\,\sigma$ level. The significance

by the *Key Project* and *Sandage/Saha*) can be ruled out at the $1.85\,\sigma$ level, and that Stanek et al. can be ruled out at some unspecified amount greater than $1.85\,\sigma$. The significance of this conclusion, though, is rendered moot by the neglect of the uncertainties associated with the individual residuals in the Ferrarese et al. analysis.

[3]We employed the same quality, color, and period cuts employed by the original authors, when drawing up the Cepheid sample of Table 1.

of this conclusion can be improved in the future with the addition of further calibrators in the $\mu_\circ = 31$ regime, provided reasonable numbers of PC Cepheids can be uncovered (i.e., distant $\mu_\circ > 32$ galaxies are not required).

EDITOR: PLACE TABLE 1 HERE.

3. Summary

We have undertaken a simple, empirical, test of the suggestion of Mochejska et al. (1999) and Stanek & Udalski (1999) that blending has seriously compromised the extragalactic Cepheid distance scale as measured by the *HST Key Project on the Extragalactic Distance Scale* and the *Sandage/Saha Type Ia SNe Calibration Team*. Mochejska et al., Stanek & Udalski, and Paczynski (1999) have each speculated that the magnitude of this systematic effect could be as large as ∼0.2 mag (i.e., ∼10%), meaning that both Hubble Constant teams have overestimated $H_\circ$ by the same amount.

The distributions of both the Tully-Fisher residuals and V-band Type Ia SNe corrected peak luminosities, for their respective nearby calibrators, show no discernible dependence upon distance. This behavior is consistent with both Hubble Constant teams' inherent assumption that blending plays a negligible role in the global error budget, and does not support the Mochejska et al. (1999) and Stanek & Udalski (1999) blending scenario. Formally, the Type Ia SNe corrected peak luminosities allow us to reject the Stanek et al. blending scenario at the $2.2\,\sigma$ level, assuming a corrected V-band peak luminosity zero point $\gtrsim -19.5$. If the SNe zero point is 0.16 mag brighter than currently assumed, statistically acceptable fits for the blending model are possible. However, the probability of reproducing the small scatter of the data about a zero-slope line with $\mathrm{M}_V^{\mathrm{corr,ZP}} = -19.46$ (the weighted mean value) is sufficiently low in this latter case that we can still rule out the model at the $\sim 2\sigma$ level. We present evidence that the uncertainties in the SNe peak luminosity may be overestimated by as much as a factor of two; if so, the blending hypothesis can be ruled out at the 2σ level regardless of SNe zero point. The absence of a systematic offset between Cepheid distance moduli derived from the higher resolution Planetary Camera and the Wide Field Camera for galaxies with suitably large $\mu_\circ$ also rules out the blending model at the 2.2σ level.

It seems likely that the discrepancy between the Stanek et al. prediction and the data, as we have discussed in this paper, is due to the high stellar background associated with the LMC and M31 fields used

in their analyses; these background levels are *not* representative of the more distant *HST* WFC frames. While it is almost certainly true that *some* fields/galaxies have been compromised by blending effects, this does *not* appear to be a global phenomemon which has compromised the Cepheid-based distance scale.

We note in passing that our *empirical* test results are supported on *theoretical* grounds by the artificial star tests described by Ferrarese et al. (2000) - these tests suggest that the blending bias is $\sim$0.02 mag, even in the most crowded *HST* WFC fields.

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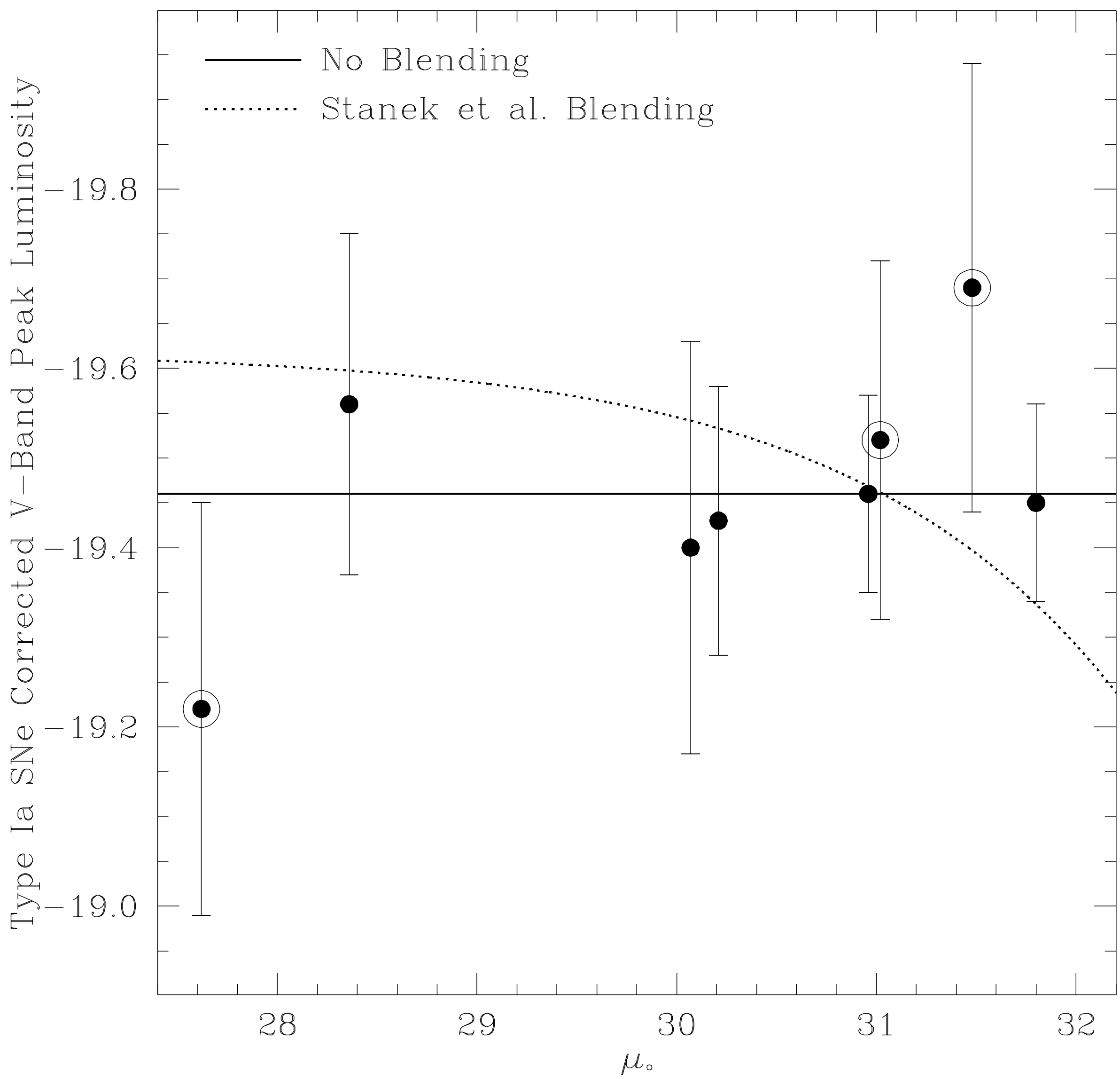
Fig. 1.— Distribution of V-band peak luminosities (corrected for light curve shape) for the 8 Type Ia SNe calibrators used by Gibson et al. (2000). The uncertainties reflect those associated with the SNe photometry, light curve shape, line-of-sight reddening and host-galaxy period-luminosity dispersion, as defined by entry 'l' in Table 7 of Gibson et al. (2000). The three calibrators with sub-standard photometry or light curve quality (SN 1972E, 1960F, and 1974G) are denoted with large open circles. The solid horizontal line represents the weighted mean of all 8 calibrators (corresponding to $\mathrm{M}_V^{\mathrm{corr,ZP}} = -19.46$), and is the expected locus if blending is negligible, as has been implicitly assumed by both the *HST Key Project on the Extragalactic Distance Scale* and the *Sandage/Saha Team*. The dotted curve represents the predicted behavior under the "Stanek et al." (i.e., Mochejska et al. 1999 and Stanek & Udalski 1999) blending hypothesis, with an adopted zero point of $\mathrm{M}_V^{\mathrm{corr,ZP}} = -19.62$; this latter zero point yields an acceptable statistical fit to the data, albeit at a significance level lower than that favored by the "no blending" hypothesis.

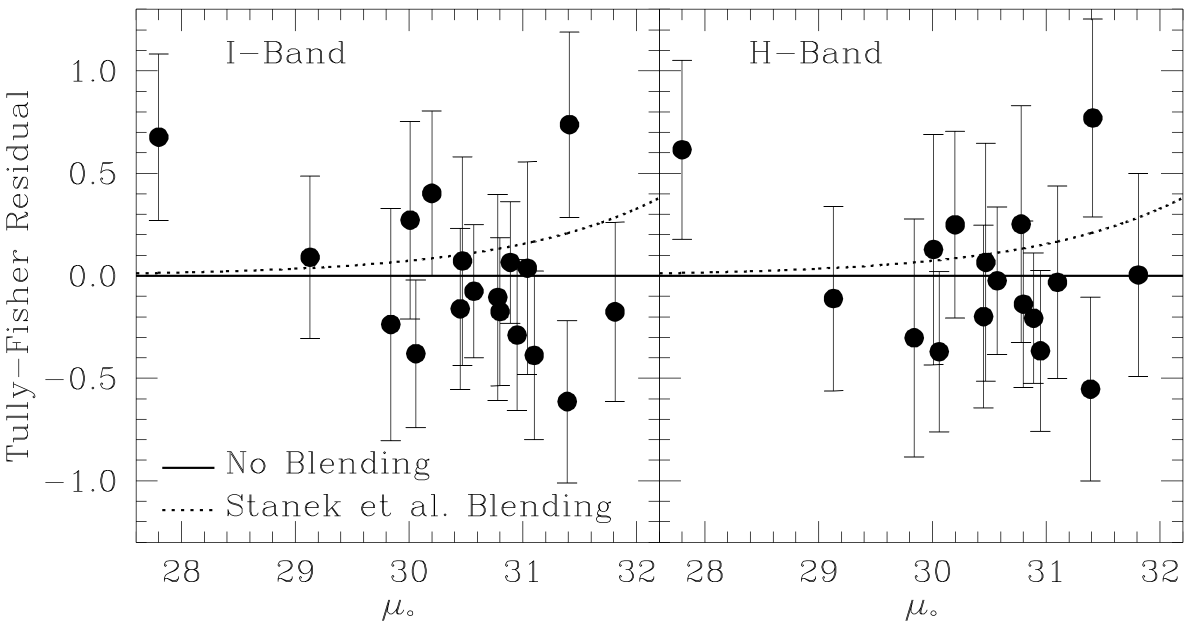
Fig. 2.— Distribution of I- (left panel) and H-band (right panel) Tully-Fisher residuals for the 18 *HST*-observed calibrators used by Sakai et al. (2000). The uncertainties reflect those of the photometry and line width for the calibrator in question (from Table 2 of Sakai et al.), as well as that of the intrinsic dispersion of the I- and H-band Tully-Fisher relations (also from Sakai et al.). The solid horizontal line represents the expected locus about which scattering should occur if blending is negligible, as has been implicitly assumed by both the *HST Key Project on the Extragalactic Distance Scale* and the *Sandage/Saha Team*. The dotted curve represents the predicted behavior under the "Stanek et al." (i.e., Mochejska et al. 1999 and Stanek & Udalski 1999) blending hypothesis; the $y-$intercept for this curve is not necessarily zero. Formally the data are completely consistent with a line of zero slope, but the blending model is discrepant at worst at the 1σ level.

Table 1. Differential Test of Blending at the Distance of the Virgo Cluster

Galaxy	$\mu_\circ$(PC)[a]	$\mu_\circ$(WF)[a]	$\mu_\circ$(PC)$-\mu_\circ$(WF)
NGC 1365	31.307±0.127 (9)	31.305±0.090 (25)	+0.002±0.156
NGC 4536	30.851±0.097 (6)	30.886±0.046 (21)	−0.035±0.167
NGC 4496A	30.980±0.104 (6)	30.949±0.043 (45)	+0.031±0.113
NGC 4321	31.154±0.181 (6)	30.960±0.070 (35)	+0.194±0.194
NGC 4548	30.990±0.034 (4)	31.009±0.065 (20)	−0.019±0.073
		Weighted Mean	+0.002±0.049
		Stanek et al. Blending Prediction	+0.11

[a]The number of Cepheids employed in the period-luminosity fitting is noted in the parentheses adjacent to the true distance modulus.


No Blending
Stanek et al. Blending
Type Ia SNe Corrected V–Band Peak Luminosity
−19.8
−19.6
−19.4
−19.2
−19.0
28
29
30
31
32
$\mu_\circ$


I–Band
H–Band
Tully–Fisher Residual
1.0
0.5
0.0
−0.5
−1.0
No Blending
Stanek et al. Blending
28
29
30
31
32
$\mu_\circ$